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Neutrinoless Double Beta Decay with R-parity Violation

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Abstract

We consider the recently observed neutrinoless double beta decay in the context of the minimal supersymmetric standard model with R-parity violating couplings $\lambda^{'}$. We observe that most of current experimental bounds on R-parity violating couplings do not exclude the possibility that neutrinoless double beta decay is caused by R-parity violation. But if we consider $K-\bar{K}$ oscillation, we observe that we have to make R-parity violating couplings generation-dependent to accomodate with the observed neutrinoless double beta decay.

Recently evidence for neutrinoless double beta decay has been found by the HEIDELBERG-MOSCOW double beta decay experiment [1]. The half-life of ^{76}Ge is reported to be

$$T^{0\nu}_{1/2} = (0.8 - 18.3) \times 10^{25}\mathrm{yr}. \tag{1}$$

This means that, lepton number is broken in nature. In the Standard Model(SM), lepton number is conserved, and this evidence becomes signature for physics beyond the SM.

We can realize lepton number violation in the R-parity violating Minimal Supersymmetric Standard Model (MSSM) (for reviews, see [2]). The R-parity violating couplings are:

$$W = \lambda_{ijk} L_i L_j E^c_k + \lambda^{'}_{ijk} L_i Q_j D^c_k + \lambda^{''}_{ijk} U^c_i D^c_j D^c_k \tag{2}$$

These terms violates lepton number and baryon number simultaneously, and thus lead to rapid proton decay. So we must forbid some or all of these terms. Usually, to achieve that, a Z_2-symmetry called as "R-parity" is imposed. R-parity is defined as

$$R_p = (-1)^{3B+L+2S}, \tag{3}$$

where B is the baryon number of the particle, L is the lepton number of the particle and S is the spin of the particle. If we impose R-parity, all the couplings in equation (2) are forbidden , and no dangerous phenomena occur.

But there is another possibility. Z_3-symmetry is anomaly-free discrete gauge symmetry, and can protect proton from rapid decay [3]. This symmetry forbids baryon number violation, but allows lepton-number violation. So it is worthwhile to investigate the lepton-number violating phenomena as resultants of a Z_3-symmetry [4]. The charge assignment of this Z_3-symmetry is shown in table 1.

Neutrinoless double beta decay was considered in the context of the MSSM with lepton-number violating R-parity [5, 6]. Detailed calculations for the neutrinoless double beta decay rate including nuclear matrix elements was done in [6]. When

particle	Q	U^c	D^c	L	E^c
charge	1	α^2	α	α^2	α^2

Table 1: Charge assignment under the discrete gauge symmetry. $\alpha^3 = 1$.

only λ' couplings are considered, the Feynman diagrams contributing to the neutrinoless double beta decay are drawn in figure 1. Since squark- and gluino-mediated process dominates, we drop the contribution from neutralino- and slepton-exchange diagrams [6].

Following reference [6], the recent result yields the following constraints:

$$1.6 \times 10^{-4} \left(\frac{m_{\tilde{q}}}{100\text{GeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{100\text{GeV}}\right)^{1/2} < \lambda'_{111} < 3.6 \times 10^{-4} \left(\frac{m_{\tilde{q}}}{100\text{GeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{100\text{GeV}}\right)^{1/2}, \quad (4)$$

where we assume $m_{\tilde{d}_R} = m_{\tilde{u}_L} \equiv m_{\tilde{q}}$.

By scanning the parameter region $100\text{GeV} < m_{\tilde{q}} < 2000\text{GeV}$, $200\text{GeV} < m_{\tilde{g}} < 2000\text{GeV}$, we make a contour plot of allowed values of λ'_{111}. It is shown in figure 2. Here we have conservatively adopted $m_{\tilde{g}} > 200\text{GeV}$. This figure shows the allower region of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ for given values of λ'. You can see that as λ' couplings become smaller, The allowed region of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ is lowered. This is because if squark and gluino masses are heavy, their contribution to neutrinoless double beta decay becomes small.

It is interesting to compair the combined constraint on λ' v.s. squark and gluino masses obtained here, with those due to other experimental results. There are many experimental results which can constrain λ'. Hereafter, we study them in detail.

For example, the existence of R-parity violation leads to a violation of universality of quark and lepton couplings to the W boson. In the quark sector, the R-parity violating couplings $\lambda'_{ijk} L_i Q_j D^c_k$ gives an additional contribution to quark semileptonic decay (e.g., in nuclear β decay) like muon decay. The effective couplings becomes:

$$\frac{g^2}{8m_W^2}[V_{ud} + r'_{11k}(\tilde{d}^k_R)], \quad (5)$$

where λ'_{11k} is defined as:

$$r'_{11k}(\tilde{l}) = \frac{m_W^2}{g^2}\frac{|\lambda_{ijk}|^2}{m_{\tilde{l}}^2}. \tag{6}$$

The CKM matrix elements are experimentally determined from the ratio of the $Q \to qe\nu_e$ to $\mu \to \nu_\mu e\nu_e$ partial widths. The experimental value is related to theoretical quantities by

$$|V_{ud}|^2_{\rm exp} = \frac{|V_{ud} + r'_{11k}(\tilde{d}^k_R)|^2}{|1 + r_{12k}(\tilde{e}^k_R)|^2}, \tag{7}$$

where r_{12k} is defined like r'_{11k}. A comparison with the experimental value:

$$\sum_j |V_{ud_j}|^2_{\rm exp} = 0.9979 \pm 0.0021 \tag{8}$$

yields the limit [7]

$$|\lambda'_{11k}| < 0.03 \left(\frac{m^k_{\tilde{d}_R}}{100\text{GeV}}\right). \tag{9}$$

at the 2σ level.

This does not exclude the possibility that R-parity violation is responsible for neutrinoless double beta decay. For example, for $m_{d_R} = m_{\tilde{q}} = 500$GeV, This limit becomes $|\lambda'_{11k}| < 0.15$, which is compatible with the allowed values of λ'_{111} shown in figure 2.

The decay rate of pion into electron and muon is also changed in the presence of R-parity violating couplings. The ratio $R_\pi \equiv \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ is

$$\frac{R_\pi(\text{expt})}{R_\pi(\text{SM})} = 0.991 \pm 0.18. \tag{10}$$

The R-parity violation gives an aeffective contribution to R_π is [7].

$$R_\pi = R_\pi(SM)\left[1 + \frac{2}{V_{ud}}[r'_{11k}(\tilde{d}^k_R) - r'_{21k}(\tilde{d}^k_R)]\right]. \tag{11}$$

Experimental value (10) set upper limit on R-parity violating couplings.

$$|\lambda'_{11k}| < 0.05\left(\frac{m_{\tilde{d}^k_R}}{100\text{GeV}}\right). \tag{12}$$

This is weaker limit compaired to equation (9), thus we can neglect this limit in this study.

The decay $K^+ \to \pi\nu\bar{\nu}$ is also modified in the presence of R-parity violating couplings [8]. We obtain:

$$\frac{\Gamma[K^+ \to \pi^+\nu_i\bar{\nu}_i]}{\Gamma[K^+ \to \pi^0\nu e^+]} = \left(\frac{|\lambda'_{ijk}|^2}{4G_F m_{\tilde{d}_{Rk}}}\right)^2 \left(\frac{|V_{CKMj1}V^*_{CKMj2}|}{|V^*_{CKM12}|}\right)^2. \tag{13}$$

So using $B(K^+ \to \pi^+\nu\bar{\nu}) \lesssim 5.2 \times 10^{-9}$ [9] and $B(K^+ \to \pi^0\nu e^+) = 0.0482$ [10], we obtain the constraint [8].

$$|\lambda'_{ijk}| < 0.012 \left(\frac{m_{\tilde{d}^k_R}}{100\text{GeV}}\right). \tag{14}$$

This constraint is stronger. For example, take $m_{\tilde{d}_{RK}} = 400\text{GeV}$, then $\lambda'_{111} < 0.05$. From the figure 2 we can see that gluino mass is constrained in the region

$$m_{\tilde{g}} \lesssim 1300\text{GeV}. \tag{15}$$

Other experiments, like $K - \bar{K}$ oscillation, and $B - \bar{B}$ oscillation gives stronger limit on the lepton number violating couplings [11]. But their limit always contain products of two λ'. Thus we cannot state strongly that we can derive upper limit on λ'_{111}. For example, $K - \bar{K}$ oscillation gives [11]:

$$\text{Re}\left[\sum_{i,j,j'} \left(\frac{100\text{GeV}}{m_{\tilde{\nu}}}\right)^2 \lambda'^*_{ij2}\lambda'_{ij'1}V^*_{j1}V_{j'2}\right] < 4.5 \times 10^{-9}. \tag{16}$$

So we cannot extract the information of λ'_{111} from $K - \bar{K}$ oscillation. Of course if we assume generation-independence of λ' couplings, we can estimate:

$$\lambda'_{111} \lesssim 10^{-4}\left(\frac{m_{\tilde{\nu}}}{100\text{GeV}}\right). \tag{17}$$

As we can see from figure 2, this is so strong constraint that we cannot explain observed neutrinoless double beta decay if we impose this constraint. So we can say that if obserbed neutrinoless double beta decay is truly the result of R-parity violation, the λ' couplings are not generation-independent.

To summarize, we consider the neutrinoless double beta decay in the context of the Minimal Supersymmetric Standard Model with lepton-number violating R-parity couplings. We observe that most of current experiments do not exclude the possibility that R-parity violation is the source of the observed neutrinoless double beta decay. But if R-parity violating couplings are generation-independent, the constraint on $K-\bar{K}$ oscillation excludes this opssibility. Generation-dependency of R-parity violating couplings is necessary to explain the $K-\bar{K}$ oscillation and the observed neutrinoless double beta decay simultaneously.

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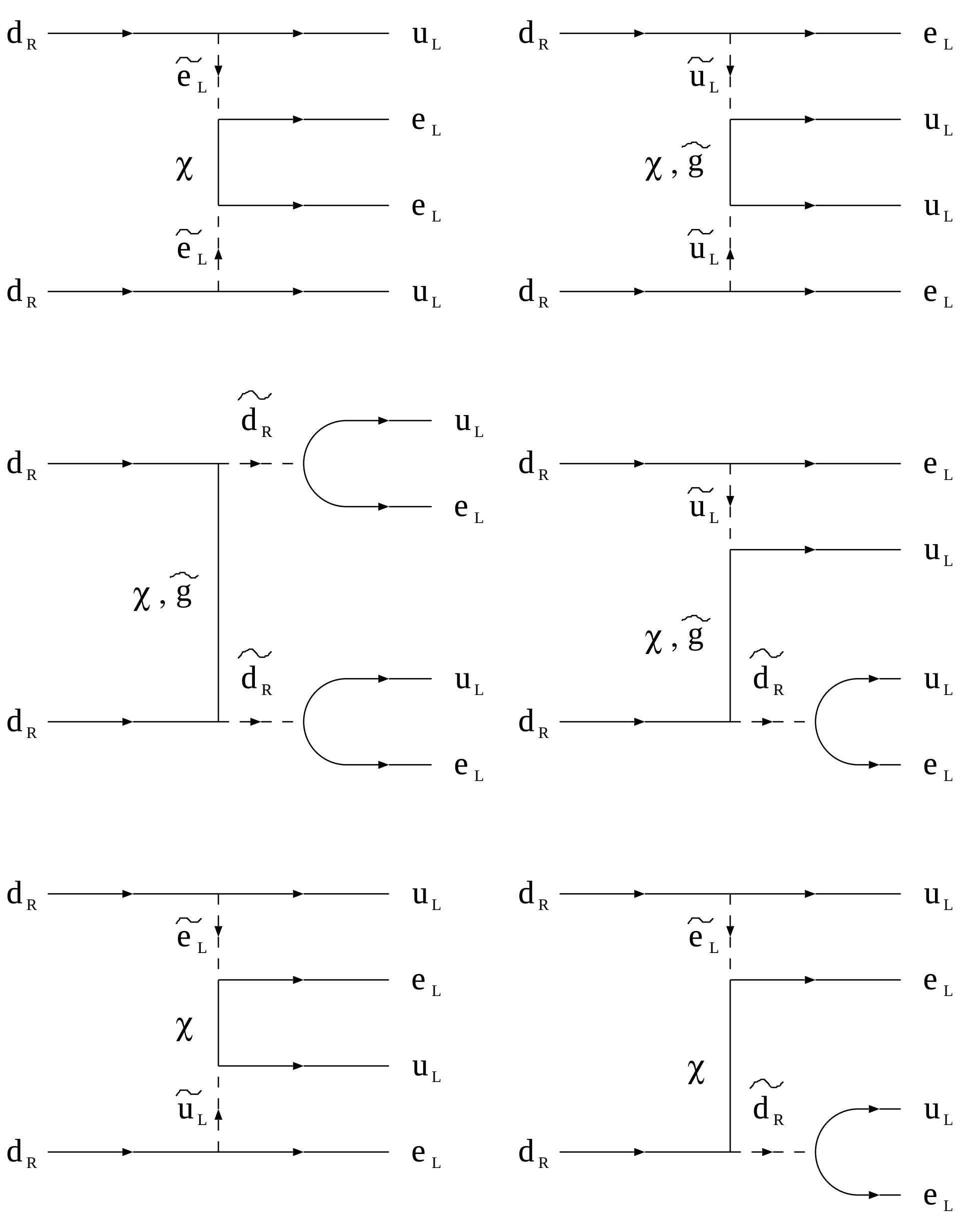

Figure 1: The processes relevant for neutrinoless double beta decay.

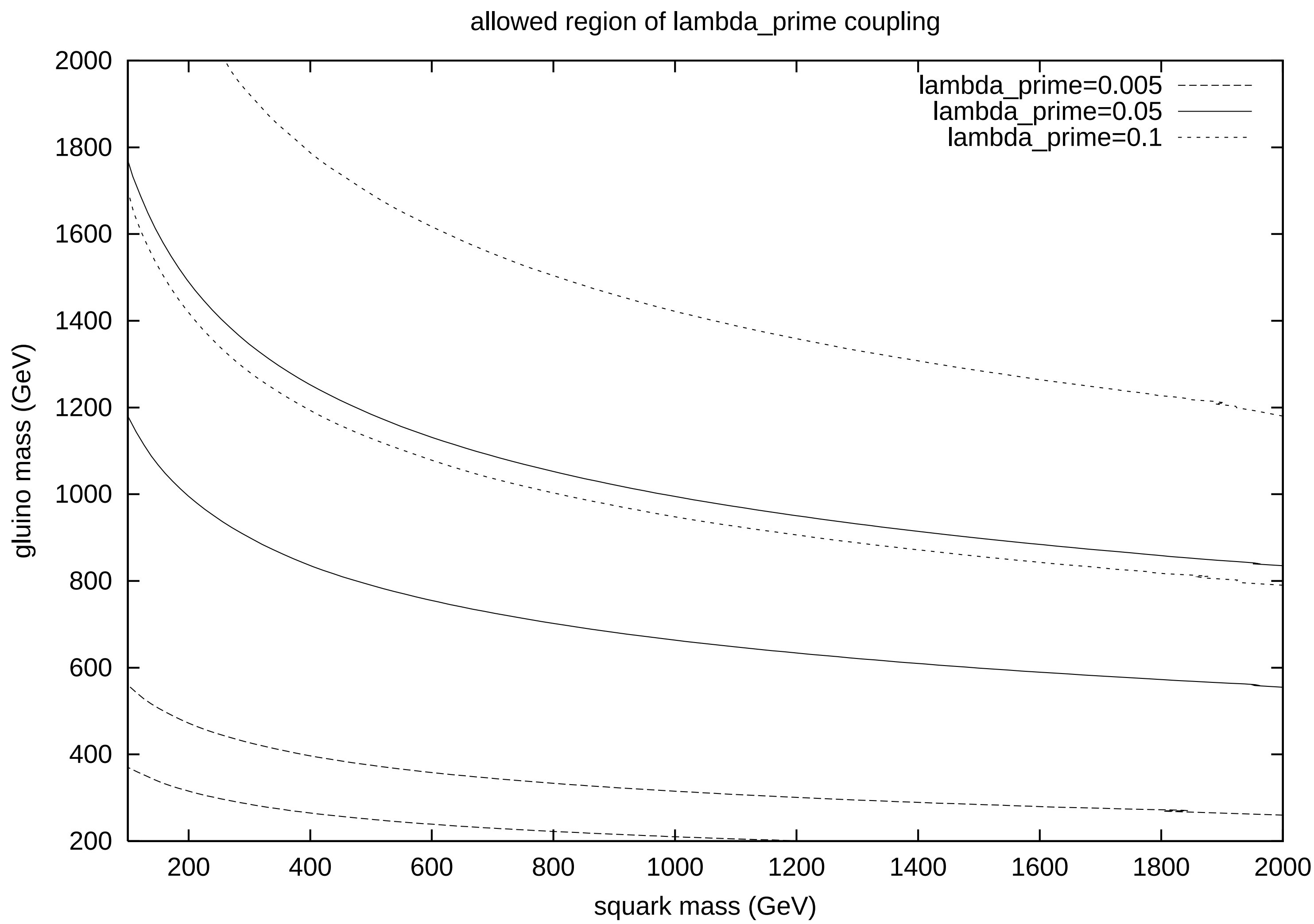

Figure 2: The allowed region for given values of λ'_{111}. Here we take $\lambda'_{111} = 0.005,\ 0.05,\ 0.1$.